

Computational study of low and high subsonic speed aerodynamic characteristics of the modified airfoil profile

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Abstract. The computational study is conducted to evaluate the low and high subsonic speeds aerodynamic characteristics of the modified airfoil profile. This profile is created using the mean-camber line of the Eppler-197 airfoil profile and the NASA LS-0013 symmetrical profile. The ANSYS FLUENT, a commercial computational fluid dynamic code, is applied to calculate the aerodynamic parameters. At low speed condition, the study is conducted at Reynolds number from 1.5×10^6 to 6.0×10^6 and angle of attack is varied from -4° to 18° . At high speed condition, the Mach number is varied from 0.4 to 0.7 while the Reynolds number is fixed at 9.0×10^6 . The range of angle of attack is taken as -2° to 6° . The results indicate that the modified profile has better characteristics than the original profile. At low speed range, the maximum lift coefficient and maximum lift-to-drag ratio are higher than the original profile. However, the minimum drag coefficient is lower. The characteristics of the modified profile at high subsonic speed is also better than the original profile. At Mach number more than 0.64, the lift coefficient and lift-to-drag ratio are also higher while drag coefficient is lower when compared with the original profile.

1. Introduction

This study is a continuous work from Ref. [1], which has studied the aerodynamic characteristics of modified airfoil profile, Eppler-197 at low subsonic speed. In the study, this profile has been modified by using some symmetrical profiles. One of these profiles is NASA LS (1)-0013. The result from the study has shown that the modified profile with NASA LS (1)-0013 profile has a pressure coefficient distribution as the same pattern as NASA supercritical airfoil (which is designed for the high subsonic speed). Therefore, this present study is set up to evaluate high subsonic aerodynamic characteristics of this modified profile. Moreover, the previous study has been done at Reynolds number 1×10^6 only. Then, this work has been also extended to study at other Reynolds numbers at low speed range. The modification airfoil profile for high speed applications is not a new concept. There are many airfoil profiles that are modified in order to improve their characteristics in high subsonic range [2-4]. In the past, these studies have been performed using wind tunnel as a primary tool. However, in the modern day, this task can be performed by numerical method or CFD code instead. There are many research works that have used CFD code to study the aerodynamic parameters at high subsonic range [5,6]. Therefore, the commercial CFD code, ANSYS FLUENT, is used as a primary tool in this study.

The aim of this study is to evaluate the aerodynamic characteristics of the modified Eppler-197 airfoil profile at the range of low and high speeds. The lift coefficient, drag coefficient and lift-to-drag ratio are the primary variables in this study. At low speed condition, Reynolds number is varied from 1.5×10^6 to



6.0×10^6 (based on the chord length) and the angle of attack varied from -4° to 18° . At high speed condition, the Reynolds number is fixed at 9.0×10^6 and the Mach number is varied from 0.4 to 0.7. The angle of attack is varied from -2° to 6° . The data of Eppler-197 original profile also comes from the simulation in this study too.

2. Airfoil modification

The mean-camber line of the Eppler-197, a low speed airfoil profile, is used as a basic camber line for the modified profile. Coordinate of this mean-camber line can be calculated by using Eqn. 1, where y is the coordinate of the Eppler-197 profile and subscript u and l mean the upper and lower surface, respectively.

$$y_c = \frac{y_u + y_l}{2} \quad (1)$$

The coordinate of the symmetrical NASA LS-0013 airfoil profile [7] is used to create the surface around the mean-camber line of the modified profile. This surface is calculated using the same method in Ref. [1]. The comparison between the original and modified profile is shown in Figure 1.

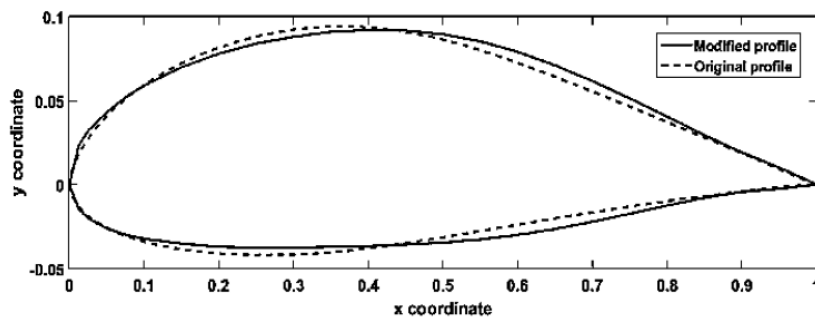


Figure 1. Comparison between the original and modified profile

3. Numerical model

The control volume around the airfoil is the C-H type domain as depicted in Figure 2. The horizontal and vertical length of the domain is 120 times and 100 times of the airfoil chord length, respectively. The internal area of the domain is divided by using structural mesh scheme. Mesh sensitivity testing is used to determine the number of meshes in the domain.

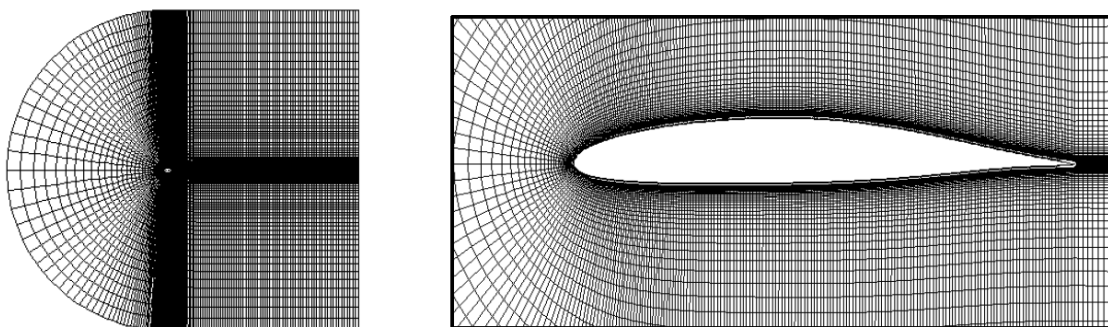


Figure 2. The control volume and the mesh shape around airfoil surface

The computational prediction is performed using commercial computational fluid dynamic code, ANSYS FLUENT 17.2. This program performs the calculation by solving the governing equations (continuity, momentum and energy) and the equation of state using the finite volume method. In order to deal with the compressibility effect in the flow field, the density-based solver (DBS) is used in this

study and the second order upwind scheme is used to calculate flow parameters. The program is set to perform the calculation until all residual values of the flow variables are lower than 4×10^{-4} and all of the aerodynamic parameters are unchanged.

In the control volume, air is selected as a medium and is assumed to be an ideal gas. The pressure farfield boundary condition is applied at outer edge of the domain. The temperature (T) is set at 300 K. In order to keep the Reynolds number at 9.0×10^6 while Mach number is varied, the density (ρ_∞) has to be changed at each Mach number. The density value is calculated using Eqn. 2 and the static pressure (P) value, which is applied at the domain boundary can be calculated by Eqn. 3. The Re is Reynolds number, μ_∞ is dynamics viscosity (kg.m/s), U_∞ is freestream velocity (m/s), c is chord length (m) that is fixed at 1 m in this study, and R is 0.287 (kJ/kg.K).

$$\rho_\infty = \frac{Re \mu_\infty}{U_\infty c} \quad (2)$$

$$P = \rho_\infty R T \quad (3)$$

At the surface of the airfoil, it is assumed that there is no relative velocity between the surface and air. Therefore, no-slip boundary is applied on the airfoil surface. The roughness of the surface is set at 0 m. The $k-\omega$ SST turbulence model is applied in this study because this model has more accuracy, higher numerical stability and can be used very well in compressible flow condition and when adverse pressure gradient occurs in the flow field [8]. In order to capture the viscous sub-layer in boundary, the y^+ value should be less than 5 [10,11]. The y^+ distance wall distance is estimated using Eqn. 4 [12]. From the estimation, the wall distance is 1.624×10^{-5} m.

$$C_f = 0.058 (Re_x)^{-0.2} \quad (4)$$

4. Mesh sensitivity and validation

The number of meshes is determined by mesh sensitivity testing. The experiment data of NACA0012-64 airfoil profile [9] is used for the test. The calculation is performed at Mach number 0.4 and angle of attack is 2° . The number of meshes is varied from 5,482 to 203,963. The results indicate that the lift coefficient and drag coefficient do not change when the number of meshes is more than 127,846 and 94,836 as being shown in Figure 3 and Figure 4, respectively. At this point, the value of lift and drag coefficient from the calculation are 0.193 and 0.0143, which agree well with the experiment data in Ref. [9].

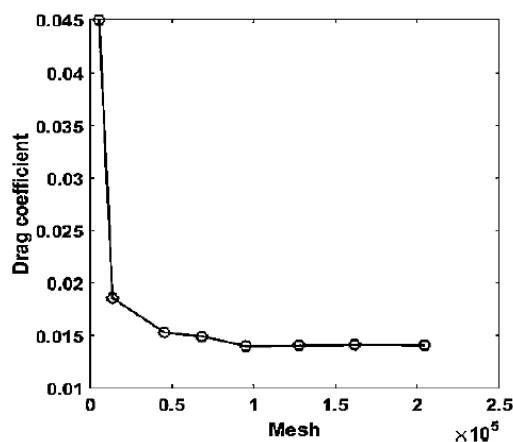


Figure 3. The relation between drag coefficient and the number of meshes

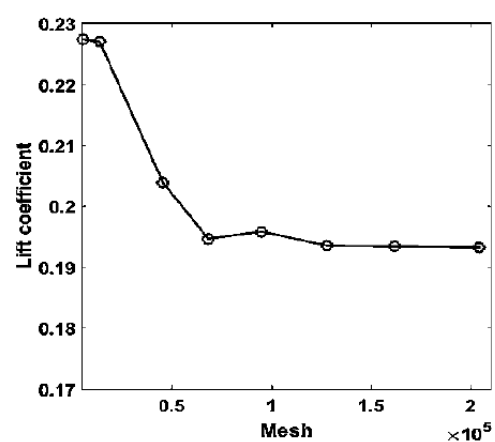


Figure 4. The relation between lift coefficient and the number of meshes

The test is further evaluated by varying the Mach number from 0.4 to 0.7 at the same angle of attack. The result shown in Figure 5 agrees very well with the experiment data. At the 127,846 meshes, the y^+ value along the upper and bottom surface of an airfoil varies from 0.010 to 0.065 as shown in Figure 6. Therefore, the condition that y^+ should be less than 5 is satisfied and the number of meshes 127,846 is used in this study.

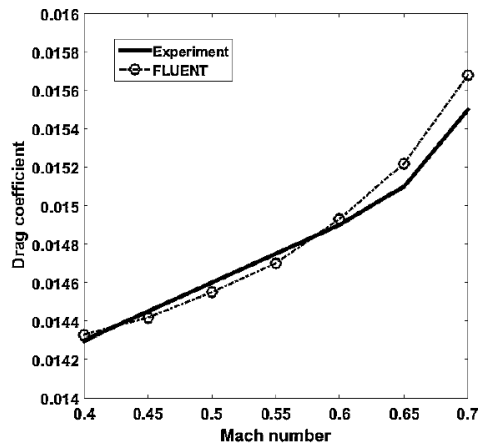


Figure 5. Comparison of drag coefficient value between experiment data and simulation

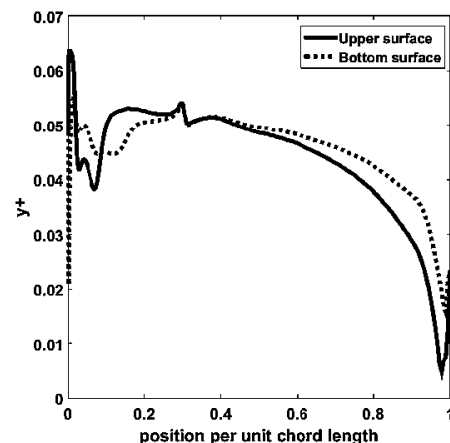


Figure 6. The y^+ value along chord length of NACA0012-64

5. Results and discussion

5.1. Low speed condition

The relation between angle of attack and lift coefficient of the modified profile shows in Figure 7. The zero lift angle of attack is set at -3.68° for all Reynolds numbers, which is nearly the same value in Ref. [1]. The slope of lift coefficient curve increases with increasing Reynolds number. The value of drag coefficient tends to decrease when Reynolds number increases as shown in Figure 8.

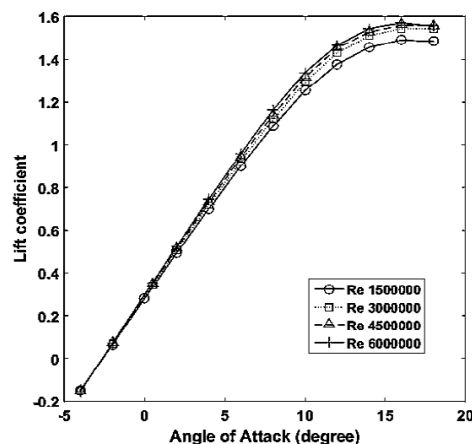


Figure 7. The relation between lift coefficient and angle of attack

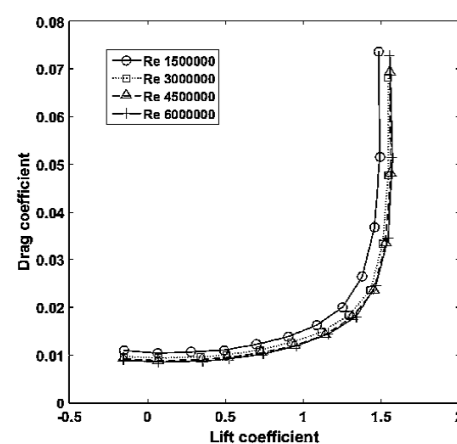


Figure 8. The relation between drag coefficient and lift coefficient

Lift-to-drag ratio increases rapidly from Reynolds number 1.5×10^6 to 3.0×10^6 as shown in Figure 9. However, this value does not change much at Reynolds numbers from 4.5×10^6 to 6.0×10^6 . When compared with the original profile, the minimum drag coefficient of the modified profile is lower at all Reynolds number range. However, the maximum lift coefficient of the modified profile is higher than

the original profile at all Reynolds number. The maximum lift-to-drag ratio of the modified profile is higher than the original profile at Reynolds number between 3×10^6 and 6×10^6 . The relations are shown in Figure 10 to Figure 12.

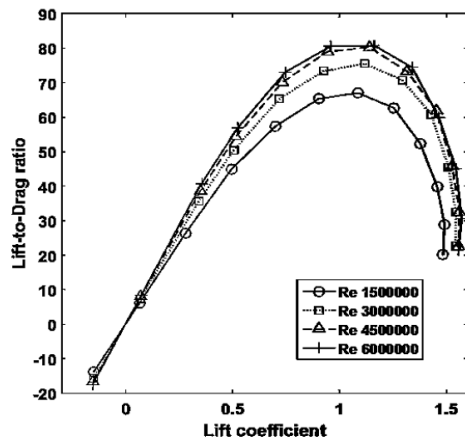


Figure 9. The relation between lift-to-drag ratio and lift coefficient

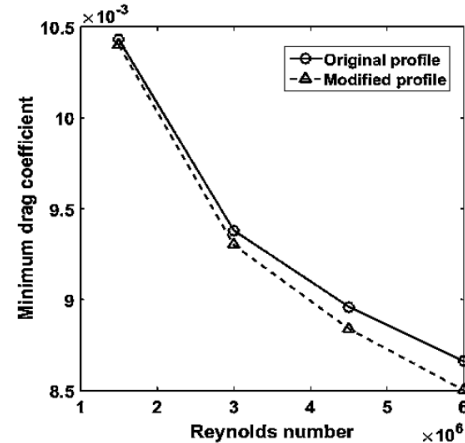


Figure 10. Minimum drag coefficient at each Reynolds number

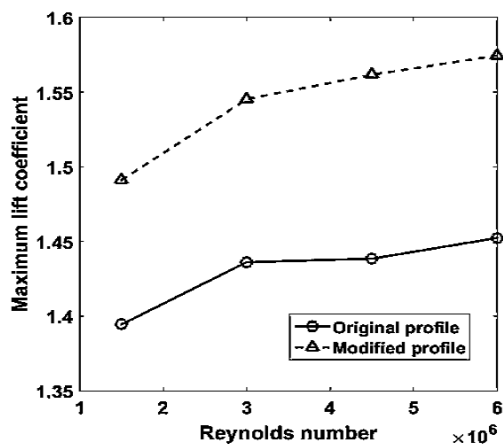


Figure 11. Maximum lift coefficient at each Reynolds number

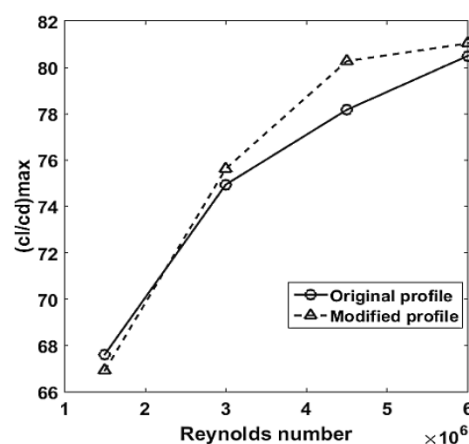


Figure 12. Maximum lift-to-drag ratio at each Reynolds number

5.2. High speed condition

The relation between lift coefficient and angle of attack at Mach number from 0.4 to 0.7 is shown in Figure 13. At Mach number lower than 0.64, lift coefficient linearly increases when angle of attack increases and the lift coefficient value of the modified profile is nearly the same as the original profile. However, at Mach number 0.64 and 0.7, the lift coefficient increases in non-linear pattern for the angle of attack above 4° and 0° , respectively. At these two points, the lift coefficient of the modified profile increases higher than the value from the original profile. The relation between lift and drag coefficient shows in Figure 14. At Mach number between 0.4 to 0.6, drag coefficient of the modified and original profile are at the same level at all lift coefficient range. When Mach number is more than 0.64, drag coefficient of the modified profile is lower than the original profile and the increase rate is also lower.

The relation between lift coefficient and lift-to-drag ratio shows in Figure 15. It shows that the value of lift-to-drag ratio tends to decrease when Mach number increases. At Mach number lower than 0.64, the value of lift-to-drag ratio of the modified profile and original profile are nearly the same at all lift coefficient range. However, at Mach number more than 0.64, the lift-to-drag ratio of the modified profile

is higher than the original profile. Figure 16 shows the comparison of pressure coefficient distribution between original and modified profile at Mach number 0.74 and angle of attack 4° . For the original profile, it shows that the normal shock wave occurs at 0.38 of the chord length on the upper surface. However, the shock wave of the modified profile occurs at 0.43 of the chord length, which is far from the leading edge more than the original profile. The delay of the normal shock wave on the modified profile causes the smaller area of separation flow behind the shock wave, as shown in Figure 17, and causes higher lift coefficient and lower drag coefficient at high Mach number as previously shown in Figure 13 and Figure 14.

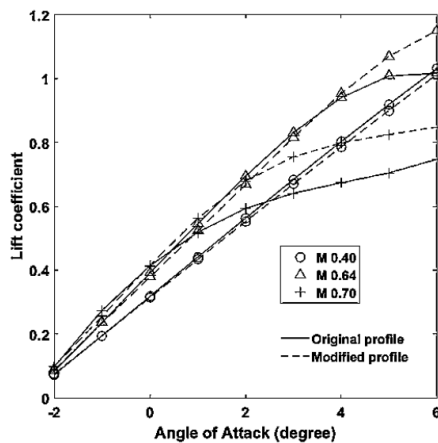


Figure 13. Lift coefficient at each angle of attack at various Mach numbers

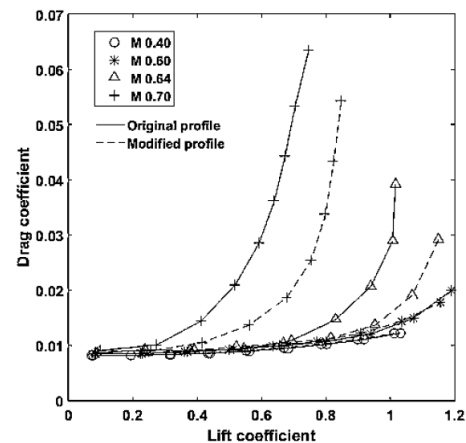


Figure 14. Relation between drag coefficient and lift coefficient at various Mach numbers

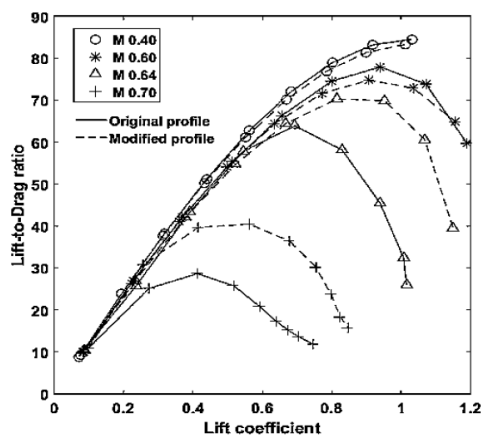


Figure 15. Relation between lift-to-drag ratio and lift coefficient at various Mach numbers

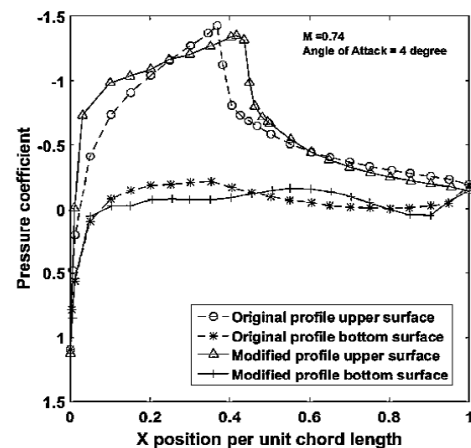


Figure 16. Comparison of the pressure distribution between original and modified profile at $M = 0.74$ and angle of attack of 4°

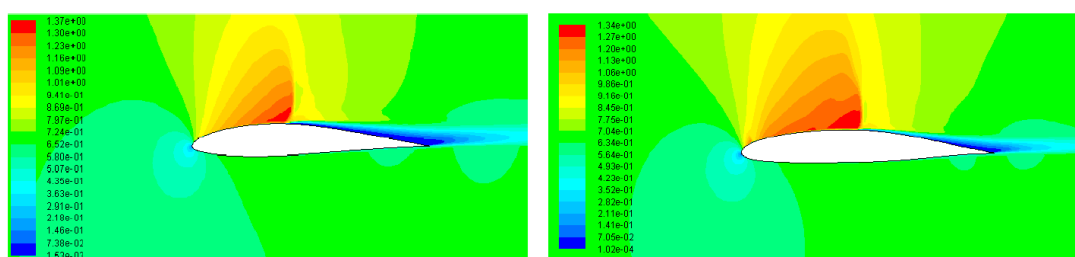


Figure 17. Comparison of the Mach contour between original (left) and modified (right) profile

6. Conclusion

The obtained results of this study lead to the conclusion that the modified Eppler-197 profile has better aerodynamic characteristics when compared with the original profile. At low speed range, maximum lift coefficient and maximum lift-to-drag ratio of the modified profile are higher than those for the original profile. However, the minimum drag coefficient is lower. The effective range of the modified profile is at Reynolds number between 3.0×10^6 and 6.0×10^6 , which all aerodynamic parameters are better than the original profile. At high speed, the modified profile also has better characteristics than the original profile when Mach number is higher than 0.64. The lift coefficient and lift-to-drag ratio have higher value while the drag coefficient is lower when compared with the original profile.

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